



Aalborg Universitet

AALBORG UNIVERSITY
DENMARK

Distributed Averaging Control for Voltage Regulation and Current Sharing in DC Microgrids

Modelling and Experimental Validation

Trip, Sebastian; Han, Renke; Cucuzzella, Michele; cheng, xiaodong; Scherpen, Jacquélien; Zapata, Josep Maria Guerrero

Published in:
IFAC-PapersOnLine

DOI (link to publication from Publisher):
[10.1016/j.ifacol.2018.12.042](https://doi.org/10.1016/j.ifacol.2018.12.042)

Creative Commons License
CC BY-NC-ND 4.0

Publication date:
2018

Document Version
Publisher's PDF, also known as Version of record

[Link to publication from Aalborg University](#)

Citation for published version (APA):

Trip, S., Han, R., Cucuzzella, M., cheng, X., Scherpen, J., & Zapata, J. M. G. (2018). Distributed Averaging Control for Voltage Regulation and Current Sharing in DC Microgrids: Modelling and Experimental Validation. In *IFAC-PapersOnLine* (23 ed., Vol. 51, pp. 242-247). I F A C Workshop Series
<https://doi.org/10.1016/j.ifacol.2018.12.042>

General rights

Copyright and moral rights for the publications made accessible in the public portal are retained by the authors and/or other copyright owners and it is a condition of accessing publications that users recognise and abide by the legal requirements associated with these rights.

- Users may download and print one copy of any publication from the public portal for the purpose of private study or research.
- You may not further distribute the material or use it for any profit-making activity or commercial gain
- You may freely distribute the URL identifying the publication in the public portal -

Take down policy

If you believe that this document breaches copyright please contact us at vbn@aub.aau.dk providing details, and we will remove access to the work immediately and investigate your claim.

Distributed Averaging Control for Voltage Regulation and Current Sharing in DC Microgrids: Modelling and Experimental Validation

Sebastian Trip^{*} Renke Han^{**} Michele Cucuzzella^{*} Xiaodong Cheng^{*}
 Jacquélien Scherpen^{*} Josep Guerrero^{**}

^{*} Jan C. Willems Center for Systems and Control. ENTEG, Faculty of Mathematics and Natural Sciences, University of Groningen, Nijenborgh 4, 9747 AG Groningen, the Netherlands. (e-mail: s.trip@rug.nl; m.cucuzzella@rug.nl; x.cheng@rug.nl; j.m.a.scherpen@rug.nl).

^{**} Department of Energy Technology, Aalborg University, Pontoppidanstræde 111, 9220, Aalborg, Denmark. (e-mail: rha@et.aau.dk; joz@et.aau.dk).

Abstract: In this paper we study a distributed control scheme, achieving current sharing and average voltage regulation in Direct Current (DC) microgrids. The considered DC microgrid is composed of several Distributed Generation Units (DGUs) interconnected, through resistive-inductive power lines, with loads. Each DGU includes a generic energy source that supplies the loads through a DC-DC buck converter. Remarkably, the proposed control scheme achieves average voltage regulation without the need of voltage measurements. An experimental validation is performed to assess the capabilities of the solution in a real network. The initial results are promising and show an additional need to compensate for partly unknown resistances present at the DGUs.

© 2018, IFAC (International Federation of Automatic Control) Hosting by Elsevier Ltd. All rights reserved.

Keywords: DC microgrids, Distributed control, Experimental validation.

1. INTRODUCTION

Recently, there has been a growing interest in the development of small electricity networks that may operate independently from the main high voltage grid. These, so-called microgrids are generally low-voltage networks and comprise various Distributed Generation Units (DGUs) as well as various loads dispersed throughout the network. Since Alternate Current (AC) has been predominant in electricity networks for many years, research initially focused on the control of AC microgrids (Cucuzzella et al. (2017a); De Persis and Monshizadeh (2018); Trip et al. (2014)). However, Direct Current (DC) microgrids are often more efficient and reliable than their AC counterparts (Justo et al. (2013)), because frequency regulation and reactive power are not needed and lossy DC-AC conversion stages are avoided (Han et al. (2017)). Typically, voltages in DC microgrids need to be regulated to be close to their nominal values, permitting a proper functioning of the various loads in the network (Cucuzzella et al. (2017b, 2018a); Jeltsema and Scherpen (2004)). Additionally, current sharing or power sharing is often desirable as it generally results in less stress on the individual DGUs and causes an overall increase in efficiency (Setiawan et al. (2016)). Conventionally, hierarchical control schemes are proposed to achieve both objectives (Guerrero et al. (2011)), where e.g. voltage setpoints at the converters are determined to achieve appropriate load sharing. Due to required scalability and Plug-and-Play capabilities of possible control schemes, while providing a fast response to changing loads, there has been a growing interest in the development of

distributed controllers, particularly aiming at current (power) sharing (Anand et al. (2013); Belk et al. (2016); Cucuzzella et al. (2018b); De Persis et al. (2018); Han et al. (2018, Early Access); Nasirian et al. (2015); Prajof et al. (2017); Wang et al. (2018); Zhao and Dörfler (2015)). On the other hand, achieving simultaneously a form of voltage regulation appears to be more challenging and provided solutions often rely on simplifying assumptions. Since current or power sharing generally not permit exact regulation of the voltages towards their desired values, various alternatives have been investigated. A popular approach is to regulate instead the average value of voltages across the whole microgrid towards a global voltage set point. This kind of voltage regulation is regularly referred to as ‘average voltage regulation’, ‘global voltage regulation’ or ‘voltage balancing’ (Nasirian et al. (2015)).

1.1 Main contributions

Recently, we have provided a novel distributed control scheme for average voltage regulation and current sharing in DC microgrids (Trip et al. (2018)). Particularly, we have provably shown that a DC microgrid comprising buck-converters and current loads, controlled by the proposed control scheme, is asymptotically stable. Notably, average voltage regulation is achieved without the need of voltage measurements. This work can be considered as a natural continuation of our efforts, in which we consider more general models and objectives. Furthermore, we provide an *experimental* validation of the proposed control scheme on a real testbed. We elaborate on a few contributions below:

1) Although the considered microgrid model is fairly standard, we provide a concise overview of a microgrid consisting of various DGUs interfaced with DC-DC buck converters and loads that consist of constant impedance, current and power

^{*} This work is part of the research programme ENBARK+ with project number 408.urs+.16.005, which is (partly) financed by the Netherlands Organisation for Scientific Research (NWO). This work is also supported by the EU Project ‘MatchIT’ (project number: 82203) and by the Chinese Scholarship Council (CSC).

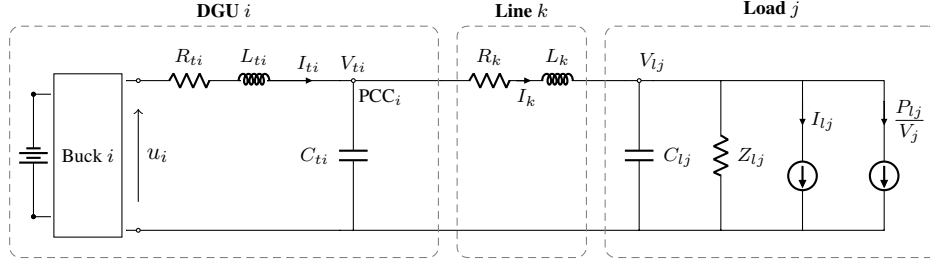


Fig. 1. The considered electrical diagram of a (Kron reduced) DC microgrid composed of two DGUs.

components. To some extent this generality is permitted because we do not aim here to provide an analytical stability assessment. Nevertheless, we think the provided exposition will be insightful and can inspire future research on the stability of the, possibly nonlinear, network we consider.

2) The proposed control scheme achieves, under the assumption of asymptotic stability, current and average voltage regulation. Although, we do not fully analyze the closed loop dynamics, the underlying rationale of the control scheme is insightful. Particularly, we emphasize that, in contrast to the common belief, voltage regulation in DC microgrids is possible *without* voltage measurements.

3) The performance of the controlled microgrid is assessed using experiments, providing promising results. Foremost, current sharing is achieved very well. Nevertheless, it appears that the feedforward compensation of the filter resistance is prone to errors, providing incentives to incorporate an additional feedback loop, to compensate for unmodelled power losses, in future extensions. Consequently, we stress that experimental validation of suggested control schemes is an important aspect in the development of robust and efficient controlled microgrids.

1.2 Outline

The remainder of this paper is organized as follows: In Section 2, the microgrid model is presented, while in Section 3 the control problem is formulated. In Section 4, the distributed control scheme is introduced. In Section 5, the experimental results are given and discussed. Finally, conclusions are provided in Section 6.

2. DC MICROGRID MODEL

In this paper we study a typical DC microgrid composed of n_t Distributed Generation Units (DGUs) and n_l loads. The various DGUs and the loads are connected to each other through m resistive-inductive (RL) power lines. We will denote, without loss of generality, the set containing all DGUs with $\mathcal{V}_t = \{1, \dots, n_t\}$ and the set containing all loads with $\mathcal{V}_l = \{n_t + 1, \dots, n_t + n_l\}$. In case we do not want to differentiate between a DGU and a load, we will also refer to them generally as a ‘node’, of which there are in total $n = n_t + n_l$. For the purpose of illustration, a schematic electrical diagram of the considered DC microgrid with one DGU and one load is depicted in Fig. 1. In the remainder of this section we will briefly discuss the mathematical description of the various components the considered DC microgrid. The descriptions of the various symbols that will be used are given in Table 1.

Distributed generation units: We first describe the dynamics of a DGU $i \in \mathcal{V}_t$. The energy source of each DGU is represented by a DC voltage source that supplies the loads through a DC-DC buck converter equipped with an output low-pass filter characterized by its impedance L_{ti} , capacitance C_{ti}

Table 1. Description of the used symbols

State variables	
I_{ti}	Generated current
V_{ti}	DGU voltage
V_{lj}	Load voltage
I_k	Line current
Parameters	
L_{ti}	Filter inductance
C_{ti}	Filter capacitance
R_{ti}	Filter resistance
C_{lj}	Load capacitance
R_k	Line resistance
L_k	Line inductance
Inputs	
u_i	Control input (converter output voltage)
Loads	
Z_{lj}	Impedance
I_{lj}	Current
P_{lj}	Power

and resistance R_t . By exploiting the Kirchhoff’s current (KCL) and voltage (KVL) laws, the equations describing the dynamic behaviour of the DGU $i \in \mathcal{V}_t$ are given by

$$\begin{aligned} L_{ti} \dot{I}_{ti} &= -R_{ti} I_{ti} - V_{ti} + u_i \\ C_{ti} \dot{V}_{ti} &= I_{ti} - \sum_{k \in \mathcal{E}_i} I_k, \end{aligned} \quad (1)$$

where \mathcal{E}_i is the set of power lines incident to the DGU i , while the control input u_i represents the buck converter output voltage¹. We refer to the point where the DGU $i \in \mathcal{V}_t$ connects to a line $k \in \mathcal{E}$ as the Point of Common Coupling (PCC).

Loads: In this work we consider so-called ZIP-loads that describe loads that can be decomposed into parts representing a constant impedance (Z_l), a constant current (I_l) and a constant power (P_l). Following again Kirchhoff’s current (KCL) and voltage (KVL) laws, the equation describing the voltage dynamics at a load $j \in \mathcal{V}_l$ is given by

$$C_{lj} \dot{V}_{lj} = \sum_{k \in \mathcal{E}_j} I_k - \frac{V_{lj}}{Z_{lj}} - I_{lj} - \frac{P_{lj}}{V_{lj}}. \quad (2)$$

In some circumstances, the capacitance at a load is negligible, i.e. $C_{lj} \approx 0$, such that (2) becomes the algebraic identity

¹ Note that u_i in (1) can be expressed as $\delta_i V_{DC_i}$, where δ_i is the duty cycle of the buck i and V_{DC_i} is the DC voltage source provided by a generic energy source at DGU i .

$$0 = \sum_{k \in \mathcal{E}_j} I_k - \frac{V_{lj}}{Z_{lj}} - I_{lj} - \frac{P_{lj}}{V_{lj}}. \quad (3)$$

However, for the purpose of exposition we assume in the remainder that the load voltages are described by (2), as it avoids a cluttered notation and the need of a careful consideration on the solvability of possible algebraic relations.

Lines: The current from DGU i to DGU j (or Load j) is denoted by I_k and we assume that the lines are resistive and inductive. Consequently, dynamics of $I_k \in \mathcal{E}$ is given by

$$L_k \dot{I}_k = (V_i - V_j) - R_k I_k, \quad (4)$$

where line k is incident to node i and node j . Note that we have dropped at the voltages, with a slight abuse of notation, the subscripts t and l .

Network: The overall DC power microgrid is represented by a connected and undirected graph $\mathcal{G} = (\mathcal{V}_t \cup \mathcal{V}_l, \mathcal{E})$. The network topology is described by its corresponding incidence matrix $\mathcal{B} \in \mathbb{R}^{n \times m}$. The ends of edge k are arbitrarily labeled with a $+$ and a $-$, and the entries of \mathcal{B} are given by

$$\mathcal{B}_{ik} = \begin{cases} +1 & \text{if } i \text{ is the positive end of } k \\ -1 & \text{if } i \text{ is the negative end of } k \\ 0 & \text{otherwise.} \end{cases}$$

Consequently, the overall microgrid system can be written compactly for nodes $i \in \mathcal{V}_t \cup \mathcal{V}_l$ as

$$\begin{aligned} L_t \dot{I}_t &= -R_t I_t - V_t + u \\ C_t \dot{V}_t &= I_t + \mathcal{B}_t I \\ C_l \dot{V}_l &= \mathcal{B}_l I - I_l - Z_l^{-1} V_l - \text{diag}(V_l)^{-1} P_l \\ L \dot{I} &= -\mathcal{B}^T \begin{bmatrix} V_t \\ V_l \end{bmatrix} - R I. \end{aligned} \quad (5)$$

Here, $V_t \in \mathbb{R}^{n_t}$ correspond to DGU voltages, whereas $V_l \in \mathbb{R}^{n_l}$ correspond to load voltages. The matrices $\mathcal{B}_t \in \mathbb{R}^{n_t \times m}$ and $\mathcal{B}_l \in \mathbb{R}^{n_l \times m}$ are obtained by collecting from \mathcal{B} the rows indexed by \mathcal{V}_t and \mathcal{V}_l respectively, i.e. $\mathcal{B} = \begin{bmatrix} \mathcal{B}_t \\ \mathcal{B}_l \end{bmatrix}$. The remaining symbols follow straightforwardly from the node and line dynamics and are diagonal matrices or vectors of suitable dimensions.

3. PROBLEM FORMULATION

In this section we formulate some common control objectives in DC microgrids. First, to avoid the overstressing of a DGU and to improve the generation efficiency, it is generally desired that the total load within the network is shared among all the various DGUs proportionally to the generation capacity of their corresponding energy sources. In the literature generally the distinction is made between current sharing and power sharing. Current sharing, on which we will focus in this work, can be formulated as $w_i I_{ti} = w_j I_{tj}$ for all $i, j \in \mathcal{V}_t$, where a relatively large value of w_i corresponds to a relatively small generation capacity of DGU $i \in \mathcal{V}_t$. This leads to the first control objective concerned with the steady state value² of the generated currents \bar{I}_t .

Objective 1a. (Current sharing)

$$\lim_{t \rightarrow \infty} I_t(t) = \bar{I}_t = W^{-1} \mathbb{1} i_t^*, \quad (6)$$

with $W = \text{diag}(w_1, \dots, w_{n_t})$, $w_i > 0$, for all $i \in \mathcal{V}_t$ and i_t^* any scalar. \diamond

² Throughout this work we denote the steady state value of a vector x by \bar{x} .

Similarly, the desire of power sharing can be formulated as $w_i V_{ti} I_{ti} = w_j V_{tj} I_{tj}$ for all $i, j \in \mathcal{V}_t$.

Objective 1b. (Power sharing)

$$\lim_{t \rightarrow \infty} V_t(t) \circ I_t(t) = \bar{P}_t = W^{-1} \mathbb{1} p_t^*, \quad (7)$$

with $W = \text{diag}(w_1, \dots, w_{n_t})$, $w_i > 0$, for all $i \in \mathcal{V}_t$ and p_t^* any scalar. The symbol \circ denotes the Hadamard product. \diamond

Another important objective within DC microgrids is to regulate the voltages. Since the voltages at the loads are generally not available within a possible control scheme, it is common practice to regulate the voltages at the DGUs close to their nominal values. This is what we will aim for in this work as well. To this end, we make the following assumption on the existence of a desired reference voltage V_{ti}^* at DGU $i \in \mathcal{V}_t$:

Assumption 1. (Desired voltages) There exists a reference voltage³ V_{ti}^* at the Point of Common Coupling (PCC), for all $i \in \mathcal{V}_t$. \diamond

Generally, achieving Objective 1a (current sharing) or Objective 1b (power sharing) does not permit a steady state voltage $\bar{V}_t = V_t^*$, since a steady state voltage $\bar{V}_t = V_t^*$ generally imposes power flows throughout the network that do not meet the load sharing objectives. For example, in case $V_t^* \in \mathcal{R}(\mathbb{1}_{n_t})$, i.e. all reference voltages are identical⁴ among the DGUs, this would result in zero power flows among DGUs that are directly connected to each other. However, there is freedom to shift all steady state voltages with the same constant value, without altering the resulting power flows since

$$\mathcal{B}^T \begin{bmatrix} \bar{V}_t \\ \bar{V}_l \end{bmatrix} = \mathcal{B}^T \begin{bmatrix} \bar{V}_t + a \mathbb{1}_{n_t} \\ \bar{V}_l + a \mathbb{1}_{n_l} \end{bmatrix}, \quad (8)$$

with $a \in \mathbb{R}$ any scalar. We therefore aim at an *average voltage regulation*, where the weighted average value of \bar{V}_t is identical to the weighted average value of the desired reference voltages V_t^* . Following the standard practise where the sources with the largest generation capacity determine the grid voltage, we select a weight of $\frac{1}{w_i}$ for all $i \in \mathcal{V}_t$, leading to the second objective.

Objective 2. (Average voltage regulation)

$$\lim_{t \rightarrow \infty} \mathbb{1}_{n_t}^T W^{-1} V_t(t) = \mathbb{1}_{n_t}^T W^{-1} \bar{V}_t = \mathbb{1}_{n_t}^T W^{-1} V_t^*. \quad (9)$$

\diamond

4. DISTRIBUTED AVERAGING CONTROL

In this section we recall and slightly modify⁵ the distributed controller proposed in Trip et al. (2018). First, we make the following assumption on the available information:

Assumption 2. (Available measurements) The generated current I_{ti} is measurable at converter $i \in \mathcal{V}_t$ and the filter resistance R_{ti} is known. \diamond

We focus on a controller achieving current sharing (see also Remark 2 for required modifications to obtain power sharing). The considered controller will be provided in an *ad-hoc* manner for the sake of exposition. Its underlying rationale will be provided thereafter. To this end, consider a distributed controller at DGU $i \in \mathcal{V}_t$ of the form

³ Often the values for V_{ti}^* are chosen identical for all $i \in \mathcal{V}$. However, the control strategy proposed later in this work permits to select also non-identical values for V_{ti}^* .

⁴ We denote the range of a matrix with \mathcal{R} and $\mathbb{1}_n$ denotes the vector of all-ones with length n .

⁵ In contrast to the controller proposed in Trip et al. (2018), we compensate for a possible filter resistance.

$$\begin{aligned}
T_{\theta_i} \dot{\theta}_i &= - \sum_{j \in \mathcal{N}_i^{com}} \gamma_{ij} (w_i I_{ti} - w_j I_{tj}) \\
T_{\phi_i} \dot{\phi}_i &= - \phi_i + I_{ti} \\
u_i &= -K_i (I_{ti} - \phi_i) + R_{ti} I_{ti} \\
&\quad + w_i \sum_{j \in \mathcal{N}_i^{com}} \gamma_{ij} (\theta_i - \theta_j) + V_{ti}^*,
\end{aligned} \tag{10}$$

where \mathcal{N}_i^{com} is the set of DGUs connected to DGU i via a communication network, with edge weights $\gamma_{ij} = \gamma_{ji} \in \mathbb{R}_{>0}$. The parameters $T_{\theta_i}, T_{\phi_i}, K_i \in \mathbb{R}_{>0}$ permit appropriate tuning of the transient response. Note that the controller is distributed as it prescribes the exchange of information on I_t and θ among neighbouring DGUs. The overall control scheme can compactly written for all $i \in \mathcal{V}_t$ as

$$T_{\theta} \dot{\theta} = -\mathcal{L}^{com} W I_t \tag{11a}$$

$$T_{\phi} \dot{\phi} = -\phi + I_t \tag{11b}$$

$$u = -K(I_t - \phi) + R_t I_t + W \mathcal{L}^{com} \theta + V_t^*, \tag{11c}$$

where $T_{\theta}, T_{\phi}, K \in \mathbb{R}^{n_t \times n_t}$ are positive definite diagonal matrices. Furthermore, $\mathcal{L}^{com} = \mathcal{B}^{com} \Gamma (\mathcal{B}^{com})^T$ is the (weighted) Laplacian matrix associated to a communication network, where \mathcal{B}^{com} is the corresponding incidence matrix and $\Gamma \in \mathbb{R}^{m_c \times m_c}$ is a positive definite diagonal matrix describing the weights on the edges. Here, m_c is the number of links in the communication network. To ensure current sharing among all converters, we make the following assumption on the communication network:

Assumption 3. (Communication network) The graph corresponding to the topology of the communication network is undirected and connected. \diamond

The microgrid (5), interconnected with the distributed controller (11), yields the overall closed-loop system

$$\begin{aligned}
L_t \dot{I}_t &= -V_t - K(I_t - \phi) + W \mathcal{L}^{com} \theta + V_t^* \\
C_t \dot{V}_t &= I_t + \mathcal{B}_t I \\
C_l \dot{V}_l &= \mathcal{B}_l I - I_l - Z_l^{-1} V_l - \text{diag}(V_l)^{-1} P_l \\
L \dot{I} &= -\mathcal{B}^T \begin{bmatrix} V_t \\ V_l \end{bmatrix} - R I \\
T_{\theta} \dot{\theta} &= -\mathcal{L}^{com} W I_t \\
T_{\phi} \dot{\phi} &= -\phi + I_t.
\end{aligned} \tag{12}$$

The consensus dynamics (11a) are frequently used in distributed controller designs aiming at current or power sharing in microgrids. Indeed, at a steady state of the system, the left-hand-side of (11a) is zero, and it follows immediately that (proportional) current sharing is achieved since $\mathcal{L}^{com} W \bar{I}_t = 0$ implies $W \bar{I}_t \in \mathcal{R}(\mathbb{1}_{n_t})$ (Objective 1a). The dynamics of ϕ given by (11b) in combination with the additional term $-K(I_t - \phi)$ in the controller output (11c) do not alter the steady state of the system, since at steady state $\bar{\phi} = \bar{I}_t$ holds. However, these terms turn out to be essential to avoid oscillatory behaviour (see Trip et al. (2018) for additional details). Finally, the term $R_t I_t + W \mathcal{L}^{com} \theta + V^*$ in (11c) is added to the controller output (11c) to have a suitable interconnection with controller state θ , guaranteeing average voltage regulation at steady state, and to compensate for the filter resistance. Indeed, notice that after pre-multiplying both sides of (12) (first line) with $\mathbb{1}_{n_t}^T W^{-1}$, realizing that $\bar{\phi} = \bar{I}_t$, yields $\mathbb{1}_{n_t}^T W^{-1} \bar{V} = \mathbb{1}_{n_t}^T W^{-1} V^*$ (Objective 2).

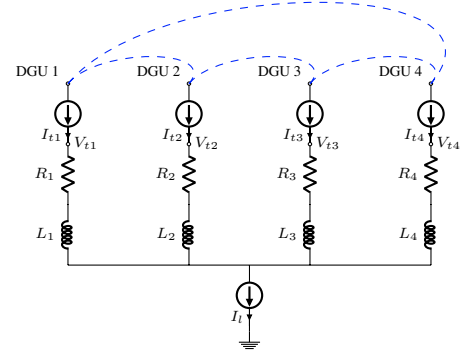


Fig. 2. Schematic representation of the experimental setup, consisting of four DGUs connected to a single load. Although the load is depicted as a current sink, it represents, depending on the considered scenario, either a constant impedance load or a constant power load. The dashed lines represent the communication network, where we have taken for the weights $\gamma_{ij} = 1$ for all $i, j \in \mathcal{V}_t$.

Remark 1. (Plug-and-Play) Note that we have not made any assumptions on the initialization of the microgrid or the controller states. Also, DGU $i \in \mathcal{V}_t$ requires only measurements of its own generated current I_{ti} and information from DGUs connected via a communication network. It is therefore expected that the proposed control schemes scales well and suitable for Plug-and-Play operation. \diamond

Remark 2. (Power sharing) To obtain power sharing instead of current sharing, we can straightforwardly adjust (10). Particularly, we can replace the currents I_{ti} in the first line (10) with the associated powers $V_{ti} I_{ti}$ for all $i \in \mathcal{V}_t$. The resulting dynamics for θ_i consequently becomes

$$T_{\theta_i} \dot{\theta}_i = - \sum_{j \in \mathcal{N}_i^{com}} \gamma_{ij} (w_i V_{ti} I_{ti} - w_j V_{tj} I_{tj}). \tag{13}$$

Remark 3. (Stability analysis) In case of a (Kron reduced) network where the loads are constant current loads, connected in parallel to the filter capacitors, asymptotic stability of the DC microgrid controlled by (11) has been proven in Trip et al. (2018). For the current work, the results from Trip et al. (2018) can be straightforwardly adapted, as long as the closed loop system is linear. For networks with constant power loads or controllers aiming at power sharing, the analysis is more challenging (see e.g. De Persis et al. (2018)) and provides an interesting future endeavour. \diamond

5. EXPERIMENTAL VALIDATION

In this section we will present an experimental validation of the proposed control scheme. Particularly, we will study the response of the controlled microgrid under changing loads. We will consider two scenarios. In the first scenario, the loads are (piecewise) constant impedances, whereas in the second scenario the loads consume a (piecewise) constant power. The experiments were performed at the Intelligent Microgrid Laboratory (Aalborg University, Denmark). A schematic overview of the experimental setup is provided in Figure 2. Furthermore, a photo of the actual setup is provided in Figure 3. As one can notice from Figure 2, the experimental setup consists of four DGUs connected via lines to a common bus to which also a single load is connected. The proposed control scheme of Section 4, is implemented in Simulink®, which is interfaced with the microgrid via a dSPACE® 1006. An overview of the electrical and used control parameters are given in Table 2. In

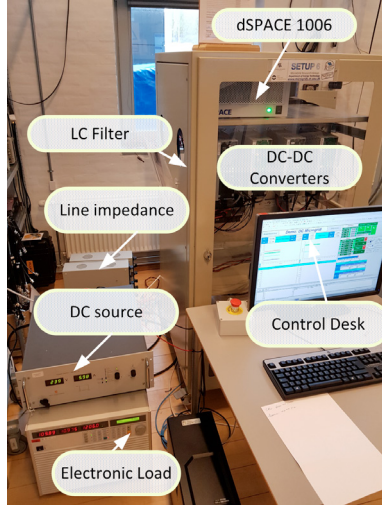


Fig. 3. A photo taken of the experimental setup.

Table 2. Electrical and controller parameters

DGU		1	2	3	4
V_{ti}^*	(V)	120.0	120.0	120.0	120.0
L_{ti}	(mH)	1.8	1.8	1.8	1.8
C_{ti}	(mF)	2.2	2.2	2.2	2.2
R_{ti}	(Ω)	0.1	0.1	0.1	0.1
Line		1	2	3	4
R_k	(Ω)	1.9	1.3	0.4	1.6
L_k	(mH)	1.2	1.5	1.2	1.7
Controller		1	2	3	4
K_i		0.5	0.5	0.5	0.5
$T_{\phi i}$		0.1	0.1	0.1	0.1
$T_{\theta i}$		1	1	1	1
w_i		2	2	4	4

the remainder of this section, we discuss the two aforementioned scenarios, of a connected constant impedance load and of a connected constant power load. Note that the experiments within both scenarios are performed with identical controller parameters and that the topology of the communication network differs from the topology of the microgrid.

5.1 Constant impedance loads

In this scenario the system is initially at steady state with an impedance load of 20Ω . After 7.3 seconds, the load is decreased to 10Ω , whereafter the load is increased again to 20Ω after 13.8 seconds. From Figure 4, it is clear the the proposed control scheme accurately achieves proportional current sharing and that the voltages remain around the nominal value of 120V.

5.2 Constant power loads

In this scenario the system is initially at steady state with a power load of 600W. After approximately 7.7 seconds, the load is increased to 1200W, whereafter the load is decreased again to 600W after 14.8 seconds. Also from Figure 5, it is clear the the proposed control scheme accurately achieves proportional current sharing and that the voltages remain around the nominal value of 120V.

5.3 Discussion

From the experimental results we can conclude that the proposed control scheme achieves the objective of current shar-

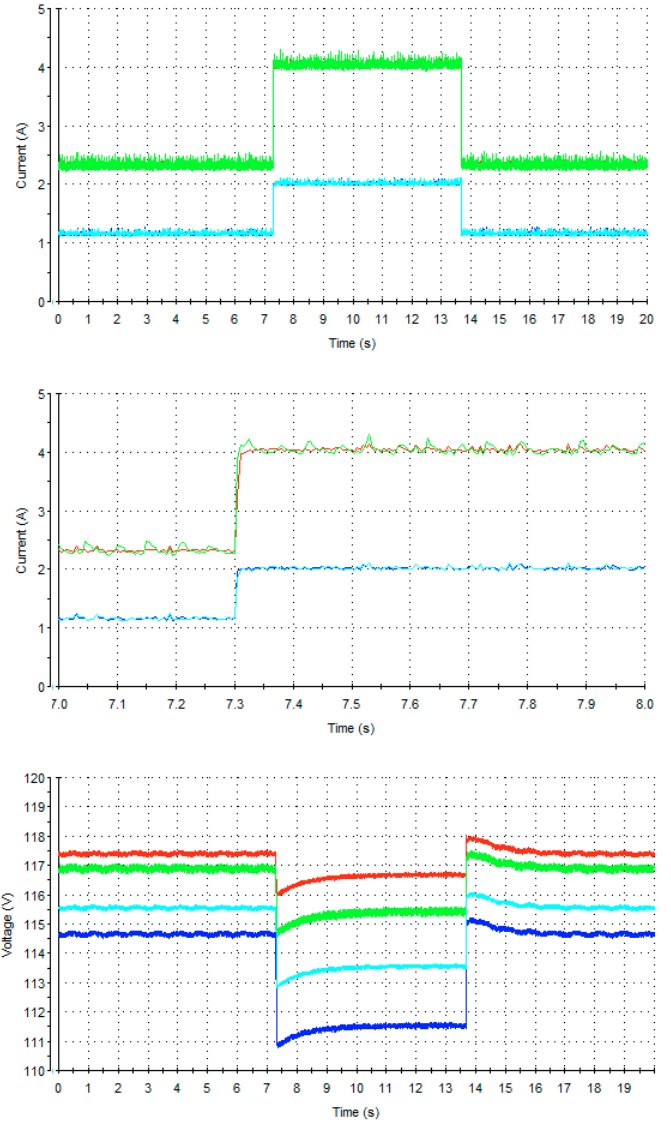


Fig. 4. Generated currents I_t and voltages V_t in case the load is a (piecewise) constant impedance load. The four different colours represent the four DGUs (see also Figure 2). Note that the middle plot zooms in at the currents, around the time when the load resistance is reduced.

ing well. And although it is remarkable that the voltages are regulated close to 120V without any voltage measurements, one can still notice from Figure 4 and Figure 5, that Objective 2 (average voltage regulation) is not properly achieved. This can be explained by that the feedforward compensation of the filter resistance is not sufficient and that, most likely, some additional resistances are present, possibly due to high frequency effects. Indeed, if we would consider an additional resistance \hat{R}_t in series with R_t , one can observe that at a steady state $\mathbb{1}_{n_t}^T W^{-1} \bar{V}_t = \mathbb{1}_{n_t}^T W^{-1} V_t^* - \mathbb{1}_{n_t}^T W^{-1} \hat{R}_t \bar{I}_t$ holds, i.e. the weighted average steady state voltage becomes lower than desired value if the generated currents become larger. This is precisely what can be seen in Figure 4 and Figure 5. We argue that therefore either the resistances need to be known more accurately, in order to permit a proper feedforward compensation, or that an additional control loop needs to be developed to compensate for the observed offset in the voltages. This is the subject of an ongoing research.

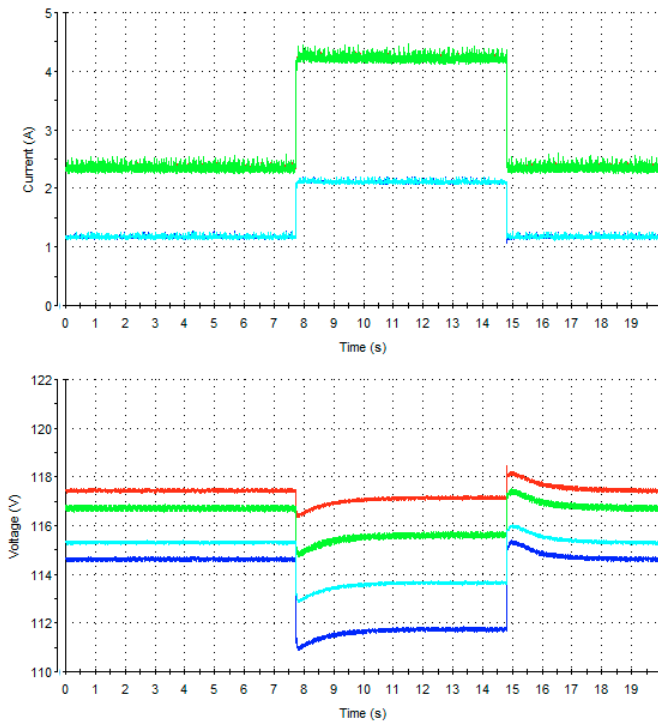


Fig. 5. Generated currents I_t and voltages V_t in case the load is a (piecewise) constant power load. The four different colours represent the four DGUs (see also Figure 2).

6. CONCLUSIONS

In this work, we have discussed a distributed control scheme to obtain proportional current sharing and average voltage regulation in DC microgrids. Notably, the suggested controller does not require voltage measurements. An experimental validation is performed to assess the capabilities of the solution in a real network. The initial results are promising and show an additional need to compensate for partly unknown resistances present at the DGUs. Interesting future research includes a stability analysis of various nonlinear realizations of the considered model. Furthermore, allowing for different converter types, such as boost converters (Cucuzzella et al. (2018a); Jeltsema and Scherpen (2004)), is a meaningful future endeavor.

REFERENCES

- Anand, S., Fernandes, B.G., and Guerrero, J. (2013). Distributed control to ensure proportional load sharing and improve voltage regulation in low-voltage DC microgrids. *IEEE Transactions on Power Electronics*, 28(4), 1900–1913.
- Belk, J.A., Inam, W., Perreault, D.J., and Turitsyn, K. (2016). Stability and control of ad hoc dc microgrids. In *2016 IEEE 55th Conference on Decision and Control*, 3271–3278.
- Cucuzzella, M., Incremona, G.P., and Ferrara, A. (2017a). Decentralized sliding mode control of islanded AC microgrids with arbitrary topology. *IEEE Transactions on Industrial Electronics*, 64(8), 6706–6713.
- Cucuzzella, M., Rosti, S., Cavallo, A., and Ferrara, A. (2017b). Decentralized sliding mode voltage control in DC microgrids. In *Proc. of the American Control Conference (ACC)*, 3445–3450. Seattle, WA, USA.
- Cucuzzella, M., Lazzari, R., Trip, S., Rosti, S., Sandroni, C., and Ferrara, A. (2018a). Sliding mode voltage control of boost converters in DC microgrids. *Control Engineering Practice*, 73, 161–170.
- Cucuzzella, M., Trip, S., De Persis, C., Cheng, X., Ferrara, A., and van der Schaft, A. (2018b). A robust consensus algorithm for current sharing and voltage regulation in DC microgrids. *IEEE Transactions on Control Systems Technology*.
- De Persis, C. and Monshizadeh, N. (2018). Bregman storage functions for microgrid control. *IEEE Transactions on Automatic Control*, 53–68(63), 1.
- De Persis, C., Weitenberg, E.R., and Dörfler, F. (2018). A power consensus algorithm for dc microgrids. *Automatica*, 89, 364–375.
- Guerrero, J.M., Vasquez, J.C., Matas, J., de Vicuna, L.G., and Castilla, M. (2011). Hierarchical control of droop-controlled AC and DC microgrids – a general approach toward standardization. *IEEE Transactions on Industrial Electronics*, 58(1), 158–172.
- Han, R., Meng, L., Ferrari-Trecate, G., Coelho, E.A.A., Vasquez, J.C., and Guerrero, J.M. (2017). Containment and consensus-based distributed coordination control to achieve bounded voltage and precise reactive power sharing in islanded ac microgrids. *IEEE Transactions on Industry Applications*, 53(6), 5187–5199.
- Han, R., Meng, L., Guerrero, J.M., and Vasquez, J.C. (2018). Distributed nonlinear control with event-triggered communication to achieve current-sharing and voltage regulation in dc microgrids. *IEEE Transactions on Power Electronics*, 33(7), 6416–6433.
- Han, R., Tucci, M., Martinelli, A., Guerrero, J., and Ferrari-Trecate, G. (Early Access). Stability analysis of primary plug-and-play and secondary leader-based controllers for DC microgrid clusters. *IEEE Transactions on Power Systems*.
- Jeltsema, D. and Scherpen, J.M.A. (2004). Tuning of passivity-preserving controllers for switched-mode power converters. *IEEE Transactions on Automatic Control*, 49(8), 1333–1344.
- Justo, J.J., Mwasilu, F., Lee, J., and Jung, J.W. (2013). AC-microgrids versus DC-microgrids with distributed energy resources: A review. *Renewable Sustain. Energy Rev.*, 24, 387–405.
- Nasirian, V., Moayedi, S., Davoudi, A., and Lewis, F.L. (2015). Distributed cooperative control of DC microgrids. *IEEE Transactions on Power Electronics*, 30(4), 2288–2303.
- Prajof, P., Goyal, Y., and Agarwal, V. (2017). A novel communication based average voltage regulation scheme for a droop controlled dc microgrid. *IEEE Transactions on Smart Grid*.
- Setiawan, M.A., Abu-Siada, A., and Shahnia, F. (2016). New technique for power sharing in DC microgrids. In *2016 IEEE 2nd Annual Southern Power Electronics Conference*, 1–5.
- Trip, S., Bürger, M., and De Persis, C. (2014). An internal model approach to frequency regulation in inverter-based microgrids with time-varying voltages. In *Proc. of the 53rd IEEE Conference on Decision and Control (CDC)*, 223–228.
- Trip, S., Cucuzzella, M., Cheng, X., and Scherpen, J. (2018). Distributed averaging control for voltage regulation and current sharing in DC microgrids. *IEEE Control Systems Letters*.
- Wang, H., Han, M., Han, R., Guerrero, J.M., and Vasquez, J.C. (2018). A decentralized current-sharing controller endows fast transient response to parallel dc-dc converters. *IEEE Transactions on Power Electronics*, 33(5), 4362–4372.
- Zhao, J. and Dörfler, F. (2015). Distributed control and optimization in DC microgrids. *Automatica*, 61, 18 – 26.